Inversion for Geoacoustic Model Parameters in Range-Dependent Shallow Water Environments from the SW06 Experiment

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LONG TERM GOALS

The ability to predict sound propagation in shallow water is limited by the knowledge of the geoacoustic properties of the ocean bottom. The long term goals of this research are: (1) to develop full field inversion methods for estimating parameters of geoacoustic models of the ocean bottom and the associated uncertainties in the model parameter values; and (2) to evaluate the performance of the geoacoustic inversion techniques for applications over a broad frequency band in range dependent shallow water environments. This work is set within the wider context of research to understand the interaction of sound with the ocean bottom and determine the critical geoacoustic parameters that affect sound transmission in shallow water.

OBJECTIVES

The recent ONR-sponsored research program in benchmarking geoacoustic inversion methods has demonstrated the maturity of present-day inversion methods against synthetic data for range-dependent shallow water environments (Chapman et al, 2003). A critical unresolved issue is the evaluation of the performance of the inversion methods for estimating geoacoustic profiles in real ocean environments. The experiments carried out in the ONR SW06 Experiment during August-September 2006 on the New Jersey continental shelf provided high quality data over a broad frequency band from 50 Hz to 20 kHz that can be used for evaluating and comparing the performance of several different techniques, including matched field inversion, reflection coefficient and bottom loss inversion, phase and group velocity dispersion and wavenumber extraction inversions. This report is focused on the matched field methods.

Although matched field inversion has proven to be very effective in many experimental scenarios, there is a remaining question of how well the methods perform in the presence of unknown variations of the environmental parameters. Uncertainties in the water sound speed due to internal waves, eddies, fronts and tidal currents that generate local inhomogeneities in the water at different spatial and temporal scales affect the inversion performance, because the matched field methods are based on acoustic propagation models that require information about the sound speed profile in the water to predict the replica fields.

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14. ABSTRACT
The ability to predict sound propagation in shallow water is limited by the knowledge of the geoacoustic properties of the ocean bottom. The long term goals of this research are: (1) to develop full field inversion methods for estimating parameters of geoacoustic models of the ocean bottom and the associated uncertainties in the model parameter values; and (2) to evaluate the performance of the geoacoustic inversion techniques for applications over a broad frequency band in range dependent shallow water environments. This work is set within the wider context of research to understand the interaction of sound with the ocean bottom and determine the critical geoacoustic parameters that affect sound transmission in shallow water.

15. SUBJECT TERMS

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The overall objectives in this research are based on use of the low and mid frequency data (50 Hz to 4.5 kHz) obtained in the SW06 experiment to: (1) Evaluate the performance of low frequency (< 1 kHz) matched field geoacoustic inversion for estimating geoacoustic models in a range dependent continental shelf break environment; (2) Investigate the impact of uncertainties in the water column sound speed profile on geoacoustic inversion: develop diagnostic tests to detect the presence of pathological internal wave environments, and determine methods for mitigating their effects on the inversion; (3) Investigate methods for geoacoustic inversion in the mid frequency band (1 – 5 kHz); (4) Determine the geoacoustic model parameters that are most critical for predicting sound propagation over the LF and MF bands. This report addresses the first three objectives that are listed above.

APPROACH

The research makes use of data recorded on the Marine Physical Laboratory vertical line arrays in collaborative SW06 experiments with Drs. W. S. Hodgkiss and P. Gerstoft. These data provide the means to evaluate the performance of inversion methods in short and long range experimental geometries, and interpret the estimated model parameters in terms of physical properties of the bottom materials, particularly, the frequency dependence of sound speed and attenuation in the sediment. The research is based on Bayesian matched field inversion of the low frequency data, and ray theory inversion of the mid frequency data.

Description of the Experiments: The shelf break location (Fig. 1) was specifically chosen to amplify the impact on geoacoustic inversion performance of uncertainties in the water sound speed profile due to internal waves, the shelf break front, a salinity/density and current that meanders near the shelf edge, and the frequent presence of warm-core eddies shed from the Gulf Stream. The vertical array consisted of 16 hydrophones equally spaced at 3.75 m, with the bottom-most sensor 8.2 m above the sea floor. A J–15 sound projector was used to generate low frequency signals in one of three modes: a set of CW tones, either four tones from 53 to 253 Hz, or five tones from 303 to 953 Hz; or an LFM sweep from 100–900 Hz. Mid frequency signals over the band 1.5–4.5 kHz were generated by a separate sound source that was used at the completion of the low frequency experiments.

Low Frequency data: This report focuses on the analysis of data from a radial track from the vertical array out to ~8 km along one of the chirp sonar survey lines. The source ship stopped at stations of 1, 3, 5 and 7 km (WP21-23 in Figure 1) and transmitted the CW tone sequences for about five minutes at a source depth of 30 m. The water depth was range independent at 79 m out to about 3 km, and gradually increased to about 83 m over the remainder of the track. Sound speed profiles (SSPs) measured in the water at each station indicated that the variation was significant over relatively short time scales and distances, due to the proximity of the shelf break (Figure 2). The high resolution chirp sonar survey revealed well-resolved structure down to about 30 m along the radial track, most prominently showing the 'R' reflector at about 20 m. This interface, which is pervasive in the region, was overlayed with alternating layers of sand and mud. In situ sediment probes were also deployed at selected sites (Jie et al, 2008). The preliminary analysis of these data indicated a sound speed value of around 1620 m/s for the sea floor sediments near the vertical array. However, the sea floor sediment type varied significantly over the region, most notably at sand ridges roughly parallel to the shelf break and a few kms north of the track.
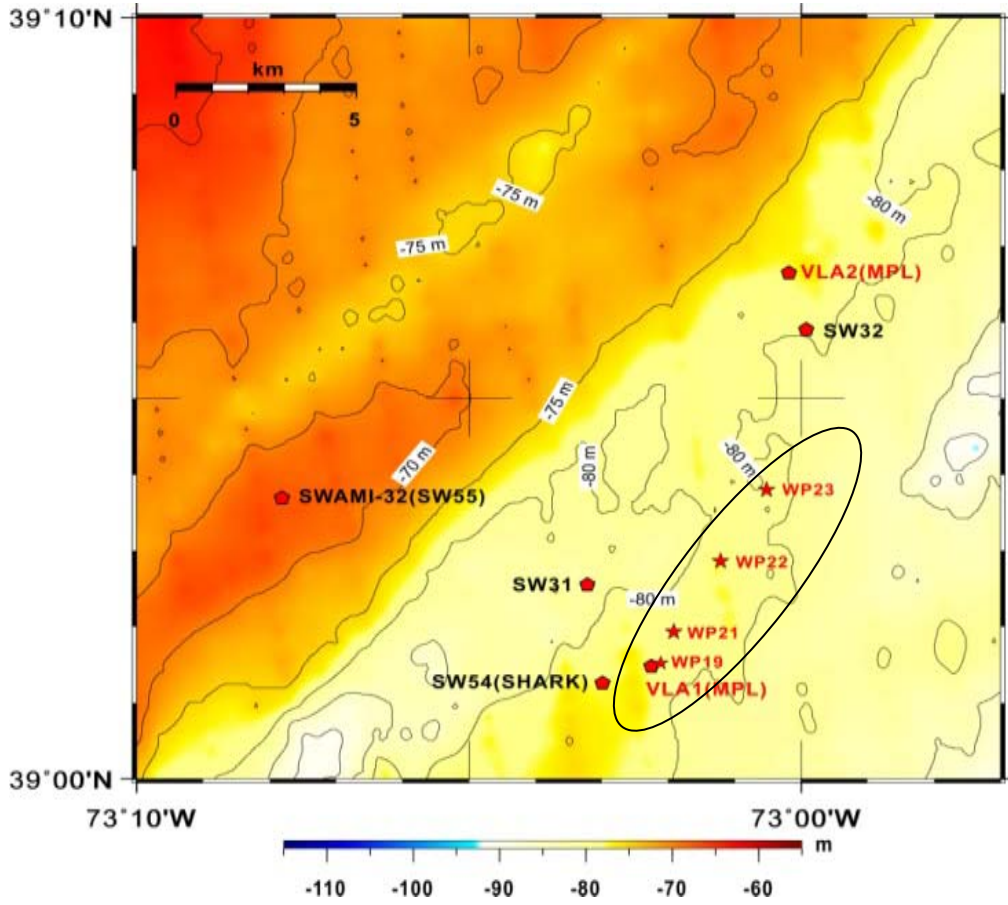
Figure 1. Location of the experiments (VLA1) on the New Jersey Shelf.

The low frequency matched field inversion is based on a Bayesian solution that combines prior knowledge about the geoacoustic model parameters with the information about the parameters that is contained in the data. The method accounts for mismatch between the measured data and calculated replica fields due to uncertainties in the ocean environment by estimating a data error covariance matrix. The covariance matrix is estimated from an ensemble of 2.6 s data windows that contain the data error information (Jiang, and Chapman, 2009). The uncertainty in the water column sound speed is accommodated by inverting for the parameters of an effective sound speed profile that is defined by a set of empirical orthogonal functions (EOFs). Two approaches for designing the EOFs are considered. The first one used only the variations in the SSPs that were observed during the time of the experiment (Figure 2). The second one included SSPs measured at other times and sites in the vicinity to capture a wider degree of variation of the profile. The geoacoustic model consisted of a sediment layer over a half space. The sediment was modelled as an inhomogeneous sound speed layer, with constant density and attenuation. The attenuation and density of the half space were held at constant values. In addition, geometric parameters of the experimental configuration and the EOF coefficients were also estimated.

Mid frequency data: An experiment was carried out at very short range (230 m; WP 19 in Figure 1) from the VLA to determine high resolution structure of the geoacoustic model. The source was lowered in the water from 25 m to 65 m in 10 m steps. The source transmitted a 1-s sweep signal over the mid-frequency band for 5 minutes at each depth. The match-filtered signal revealed sub-bottom

reflectors from the R-reflector and a weaker reflector at a shallower depth. The relative amplitudes of the reflections from the sea bottom and the R-reflector were used to estimate the frequency dependence of the attenuation in the measurement band.
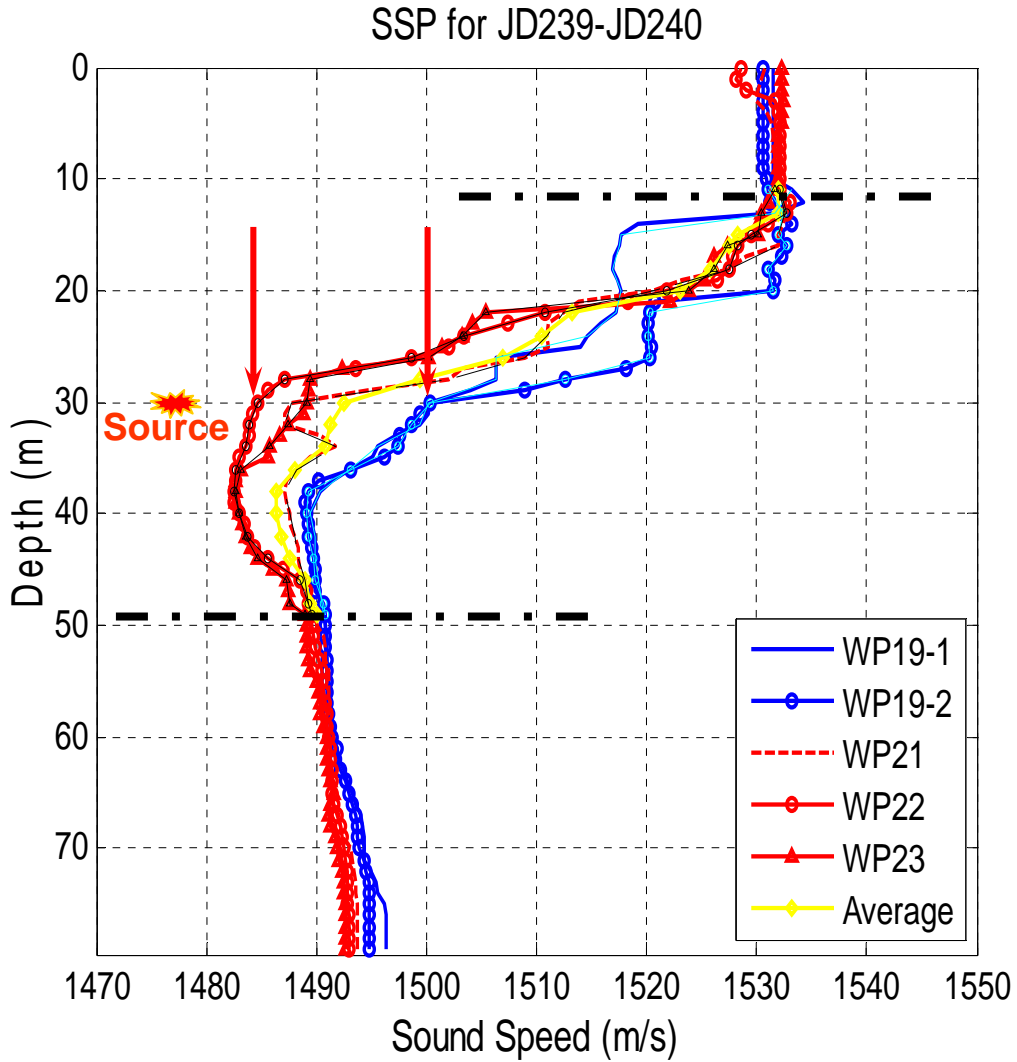

Figure 2. Sound speed measurements at the receiver (WP 19) and at the source (WPs 21-23) during the experiment. The sound speed at the source varies by ~18 m/s.

WORK COMPLETED

Matched field inversions were carried out for the low frequency data from the experiments at 1, 3 and 5 km ranges using both approaches to account for the SSP uncertainty. An inversion method was developed based on analysis of the ray amplitudes to invert the attenuation in the sediment material between the sea floor and the R-reflector, and the inversion was completed for the short-range variable-depth experiment at the VLA central site.

RESULTS

Low Frequency inversions: The estimated values for the geoacoustic parameters from the three ranges are displayed in the panels in Figure 3 that show the Bayesian marginal densities obtained for the inversion using only a limited set of SSPs to construct the EOFs. Similar results were obtained for the geoacoustic parameters using the large sample set to construct the EOFs. At a range of 1 km (WP 21), the inversion is most sensitive to the sound speeds in the upper layer of sediment and the sound speed in the basement below the R-reflector. The inversion estimated a thickness of about 22 m for the sediment layer, consistent with the expected depth of the 'R' reflector from the chirp sonar survey. Within the layer, the sound speed decreases from a value of 1640 m/s at the sea floor to around 1580 m/s at the base of the layer. The sound speed increases to about 1800 m/s across the interface at the base of the sediment layer. Preliminary analysis of data from the in situ probe measurements of sediment sound speed at the sea floor near the vertical array indicate sound speeds of ~1620 m/s. The variation with depth within the layer is consistent with results from deeper cores in the vicinity that show decreasing sound speed at depths between 3-15 m due to embedded layers of clay and silt. The sound speed increases at the 'R' reflector to ~1750-1850 m/s. Also noteworthy are the results for the attenuation, which is modeled as nonlinear over the frequency band. Reliable estimates of the attenuation coefficient and the frequency power are obtained only for the longest range of 5 km (WP 23).

Our results indicate that including a greater degree of variation in the water column SSPs to construct the EOFs did not have a significant impact on the geoacoustic parameter estimates. However, the computational efficiency of the inversion is significantly reduced for the inversion with the larger SSP set because a greater number of EOF coefficients were required to account for the greater variation in the SSPs. Two dimensional marginal densities showed that there was little or no correlation between the most sensitive EOF coefficients and the geoacoustic parameters. Strong correlations do exist, however, between the most sensitive EOFs and the geometric parameters of the experiment such as the range and source depth.

The EOF approach used here assumes that a single effective SSP can be used to focus the sound energy in calculating the replica acoustic fields for matched field inversion. From Figure 3, this assumption applies well for the data from the 1 and 5 km ranges, but not for the 3 km range (WP 22); for these data the marginal densities for the sensitive parameters are not well behaved. This breakdown is likely due to the presence of internal waves in the vicinity that cause significant local variation in the SSP. Our research is currently investigating methods to quantify the degree of SSP variation to determine the limits of our single effective profile assumption.

Mid Frequency inversions:

The matched filtered signals for one-minute averages of data for source depths of 25, 35, 55 and 65 m are shown in Figure 4. The arrival from the sub-bottom reflector is seen at times following the bottom reflected path (BR). Previously we reported the results of travel time inversion of these data to estimate the sound speed and sediment layer thickness. Here we show the results of inversion of the relative amplitudes of the sea floor and R-reflector signals to estimate the sound attenuation.   Figure 5 shows the amplitude ratio (in dB) plotted versus frequency over the mid frequency band from 1.75 to 4.5 kHz. From ray theory, the slope of the data is given by the product of the attenuation coefficient and the path length of the signal in the sediment layer (Jiang et al, 2009). Analysis of the data from four source-receiver pairs indicated a linear variation with frequency and a value of 0.1 dB/λ. This

result is consistent with other values obtained by Turgut from the chirp sonar survey and by Choi et al. from analysis of high frequency propagation data. These results suggest that a linear frequency dependence persists to frequencies as low as 2 kHz for the de-watered, clay-rich outer shelf sediment material at this site. However, the value from the short range reflection experiment is distinctly lower than the result obtained from the longer range matched field inversions (ie from WP 23, Figure 3). The source of this difference is the subject of current investigation in our research.
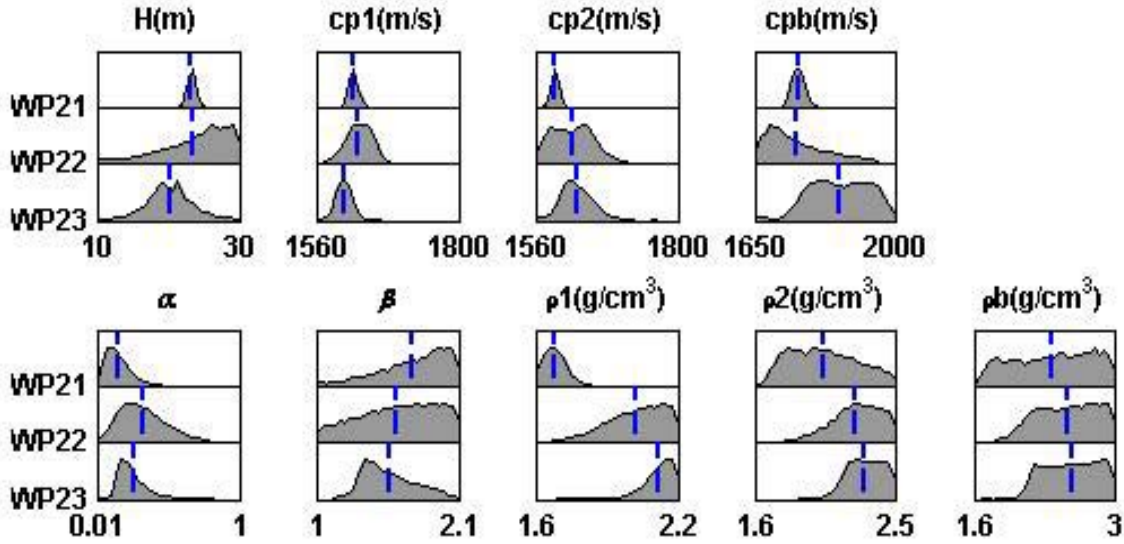

Figure 3. Marginal densities of the estimated geoacoustic model parameters for EOFs generated using a limited set of water column SSPs taken during the time of the measurement .

IMPACT/APPLICATIONS/TRANSITIONS

The research demonstrated that uncertainty in the water column sound speed has significant impact on the performance of matched field geoacoustic inversion. The results of the inversions showed that the sound speed uncertainty can be accounted for using a single effective sound speed profile defined by empirical orthogonal functions that are estimated in the inversion, assuming that the sound speed variations that are not large. It is sufficient to use a limited set of measured SSPs that contain the variations in the sound speed profile that are characteristic of the variations at the time of the experiment.

Measurements of attenuation from a short range, single bottom reflection geometry provide new estimates of the intrinsic attenuation in the outer shelf sediments. However, the values are not consistent with estimates obtained from the longer range matched field inversions. This issue is under current investigation.
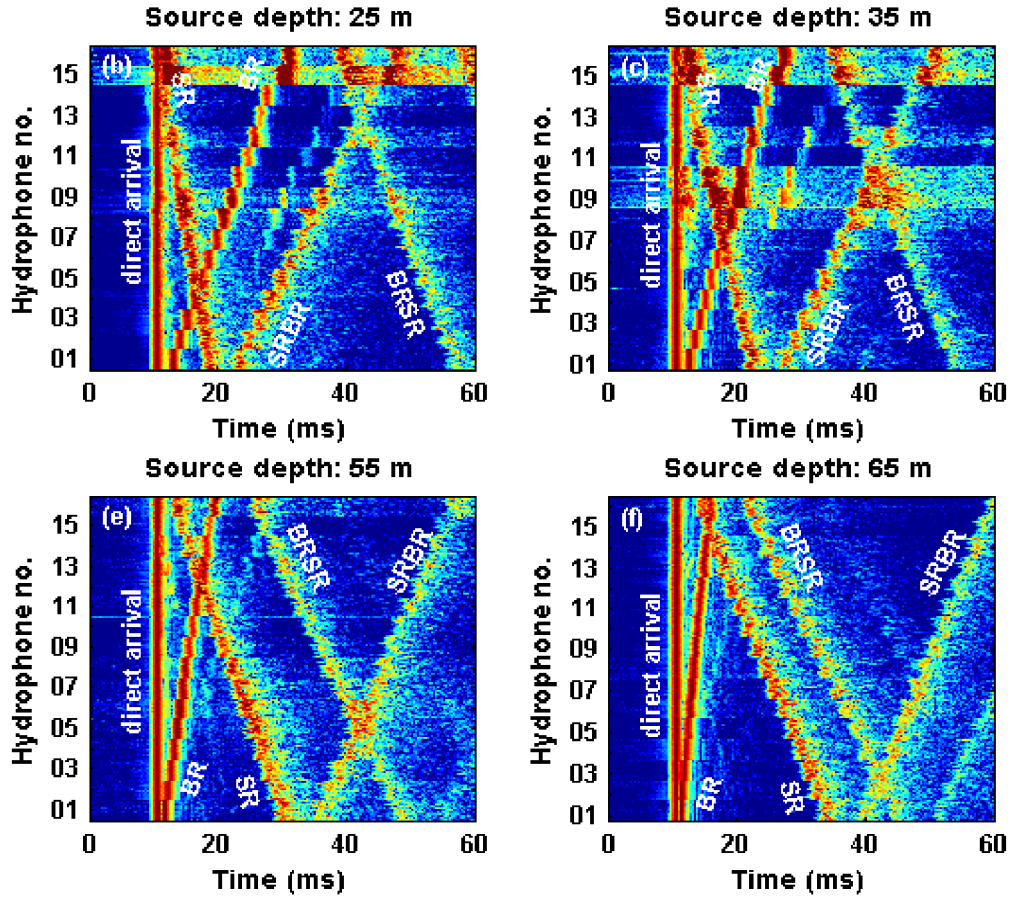
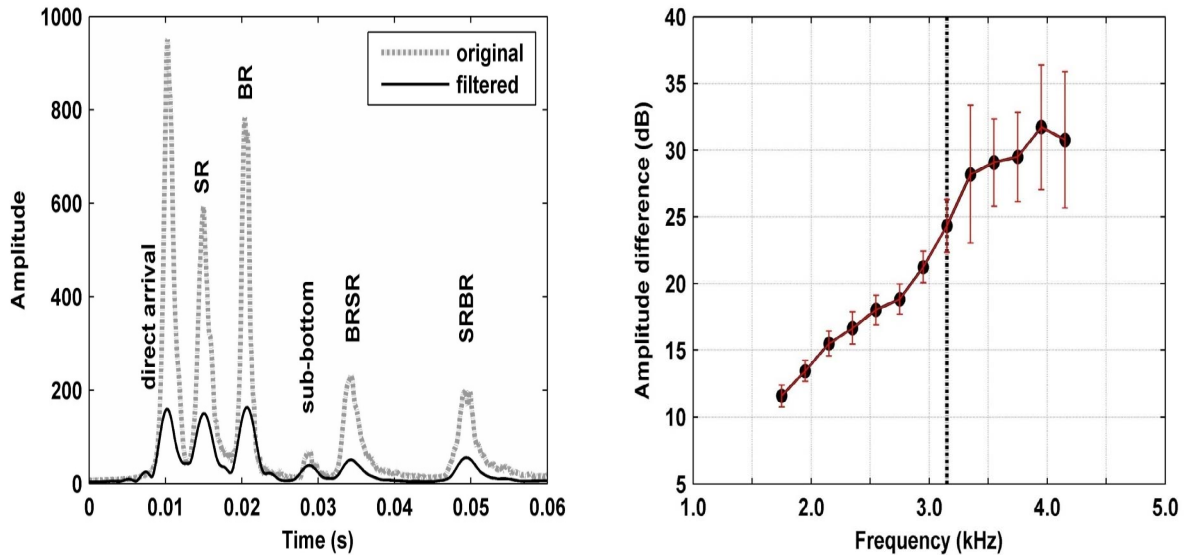*Figure 4. Matched filtered signal for mid frequency LFM sweep data.*

Figure 5. Amplitude ratio of the bottom and sub-bottom reflected signals.

RELATED RESEARCH

The experimental data from the SW06 geoacoustic experiments are high quality data that can serve as benchmark data for evaluating the performance of geoacoustic inversion methods.   My research related to the analysis and interpretation of data from the geoacoustic experiments in SW06 is connected with the research projects of the following: W. S. Hodgkiss and P. Gerstoft (MPL, SCRIPPS); D. Knobles (ARL:UT); G.V. Frisk (Florida Atlantic); K. Becker (ARL Penn State); P. Dahl and D.J. Tang (APL UW); J. Miller (University of Rhode Island), J. Goff, U of Texas at Austin and J. Lynch (WHOI).   The overall goal of this group is to apply geoacoustic inversion techniques to data that were obtained at the site near the MPL vertical line array and along the radial track from it. Comparison of the results from the different techniques will provide new understanding of the strengths and limitations of present day inversion techniques.

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